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THE INTERFERENCE METHOD OF MEASURING THERMAL EXPANSION

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ABSTRACT

This paper is in response to numerous inquiries for details of the method developed at this bureau and described in Scientific Papers Nos. 393 and 485, and several articles in outside publications. It is intended as a manual for the use of those who wish to measure thermal expansions by the interferometric method. As such, a more complete description of the apparatus and methods developed can be included than would be in order in a paper dealing primarily with the results of a particular set of measurements. The apparatus, method of making specimens, forms for taking data, and computation of data, each is the subject of a careful exposition. An appendix contains tables and special calculations.

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I. INTRODUCTION

This paper is in response to numerous requests for details of the interferometric methods, apparatus and procedure developed at this bureau and described briefly in Scientific Papers Nos. 393 and 485 and in several outside publications. It includes later developments in apparatus and technique and full information regarding procedure.

The apparatus described lends itself equally well to the determination to a high degree of accuracy of the linear expansion under equilibrium conditions, or to the determination of the continuous changes in length taking place in a material while being heated or cooled at a predetermined rate which may or may not be uniform. The results obtained by the two procedures are not always the same and it is necessary for the experimenter to consider carefully which procedure is the one which will yield the information he desires.

Since materials differ greatly in the rate with which they reach equilibrium, an investigator attempting to obtain measurements under equilibrium conditions should give careful consideration to this rate at the temperatures involved. For certain kinds of work it is the practice to hold the specimen for a sufficient length of time at each temperature where measurements are to be taken. Cases have occurred in this laboratory where equilibrium conditions were not reached even after several hours.

In the case of a material where the expansion follows the increase in temperature in a regular way an approximate value for the expansion under equilibrium conditions may be obtained by heating continuously at a slow rate and neglecting the readings taken before the heating rate becomes established. In this case it must be assumed that the lag will be constant and that only "true" thermal expansion is taking place. Strictly speaking the only true thermal expansion is where an increase in size of a material results from an increase in effective size of the constituent molecules without any change in their relative arrangement. There are, however, certain effects of change of thermal energy occurring in different substances at different temperature ranges which result in a more or less sudden and drastic rearrangement of the molecules. These appear in the thermal expansion curve as irregularities of slope sometimes amounting to an actual reversal. Such rearrangement of the molecules into different configurations may be very rapid, such as the almost instantaneous conversion of alpha into beta quartz, or very slow, such as the annealing of glass. In either case a study of their nature can be made with this apparatus by heating at a definite rate with frequent readings on the temperature and change in length. This continuous or mobile procedure is not to be considered merely a convenient method of obtaining an approximation to the same value better obtained by means of the equilibrium procedure, but may be thought of as a means of obtaining an entirely different type of information. An insufficiently rapid change of temperature often masks the information sought, hence for a complete analysis several rates should be used and the results compared.

The point to be emphasized here is that neither the "equilibrium" nor the "mobile" procedure should be used indiscriminately, but that each problem should be analyzed and a decision reached as to the type of information desired so that the more appropriate procedure may be selected.

Because of the small size of specimen and the ease and rapidity of reading, the interferometric apparatus described in this paper is particularly advantageous when the mobile procedure is selected. The small size of the specimen and simplicity of temperature control are features which recommend its use in cases where the specimen is to be held at a constant temperature until reaching equilibrium.

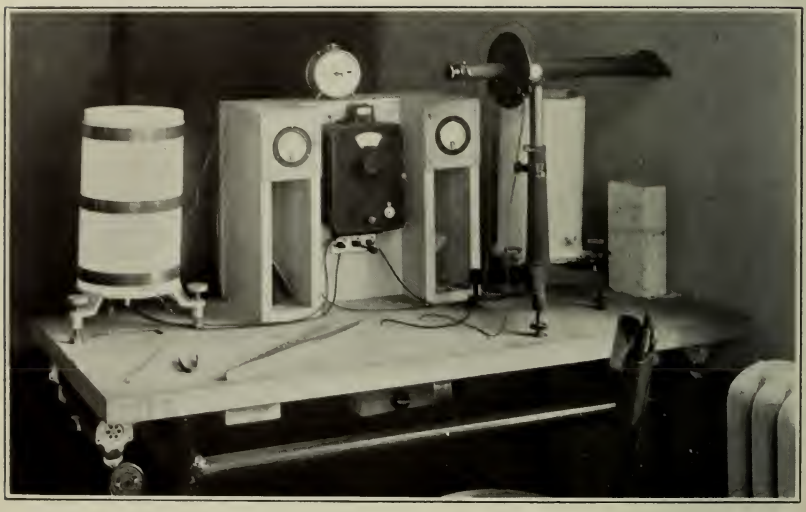

FIGURE 1.—*Assembled apparatus for thermal expansion measurements by the interference method*

II. CONSTRUCTION AND ADJUSTMENT OF APPARATUS

The apparatus consists of three main parts—a furnace for heating the specimen, a device for measuring the temperature, and a means for measuring the change in length. Figure 1 shows the set up.

1. THE FURNACE

A very satisfactory furnace of the tubular type, wound with 17 to 18 feet of chromel ribbon of 1-ohm resistance to the foot is illustrated in Figure 2. The ends of the ribbon are anchored to iron collars and either hard soldered to copper leads or carried out to the outside of the furnace and clamped to binding posts. Care must be taken that the insulation in a vertical direction is as nearly symmetrical as possible. If this is not done, there will be a temperature gradient between the thermocouple and the specimen which will give trouble.[1] The space between the heating tube and the outside of the furnace is filled with silocel or some other similar insulating material capable of standing high temperatures.

This furnace is heated by a 110-volt line current of from 1 to 5 amperes which should be controlled by means of rheostats. For nonmagnetic specimens either direct or alternating current is satisfactory. A convenient, though not necessary accessory, is a tapered wire rheostat which will take more current without overheating as the resistance is taken out. Furnaces of this type may be purchased on the market.

A small porcelain bucket is provided by means of which the specimen may be introduced into and removed from the furnace. The thermocouple is inserted through the bottom of the furnace and projects through a hole in the bottom of this bucket, so that the junction is almost, but not quite, in contact with the lower surface of B, Figure 2.

2. TEMPERATURE MEASURING APPARATUS

For temperature measurements a potentiometer set-up as shown in Figure 3 may be used. The electromotive force developed by the difference in temperature between the hot and cold junctions of the thermocouple is balanced across a galvanometer against the electromotive force of a 2-volt storage battery by means of resistances introduced by the dials of the potentiometer, the storage battery having been previously balanced against a standard cell by means of external rheostats. While the galvanometer sensitivity must drop very low to affect the accuracy of the reading, a rather close watch of the sensitiv-

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[1] In order to control the temperature gradient in the furnace, it is desirable to check the temperature indicated by the thermocouple against the temperature existing at the same time in the location occupied by the specimen. A method for approximating this is by utilizing the well-known melting points of several of the more fusible metals.

In order to do this, it is only necessary to prepare a specimen consisting of one element of the desired metal and two elements of some more refractory metal, the expansion of which is not too different from that of the fusible metal. The specimen should be of small cross section in order not to delay the melt.

It is not necessary to count the fringes, but only to watch them carefully as the expected melting point approaches and to see that the heating schedule is the same as that to be used when making regular runs. The melting point is indicated by a rapid change in width of the fringes, culminating in their entire disappearance.

Since many substances have a bad effect on the surfaces of fused quartz, it is desirable to confine these tests to a few metals which have been found to have little effect on the surfaces and the melting points of which are well known, such as:

	°C.
Tin	231.9
Zinc	419.4
Aluminum	658.9
Silver	961

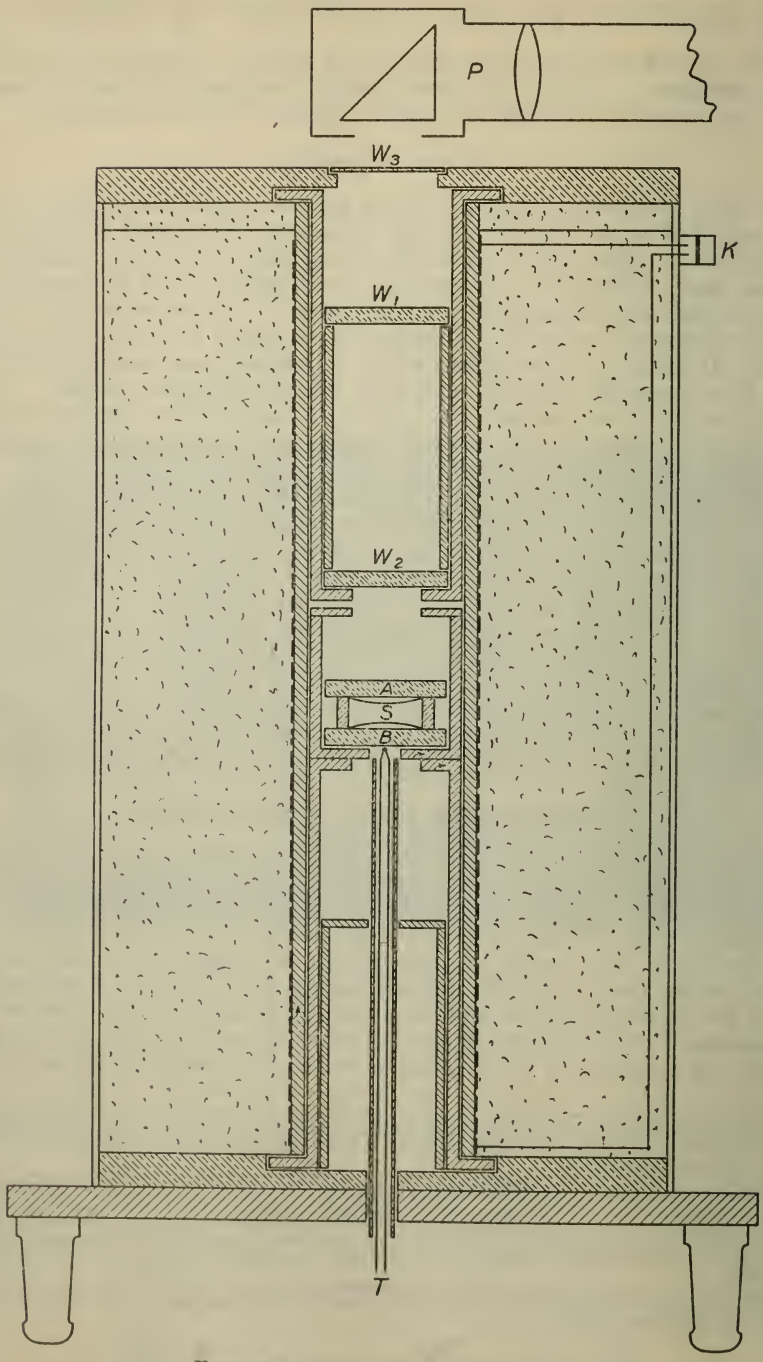

FIGURE 2.—*Cross section of furnace*

ity is desirable, because any change may be an indication of poor connections or other trouble.

A platinum, platinum-rhodium thermocouple is recommended. A table which gives the standard calibration for this kind of couple is shown on page 73. For use from room temperature to 1,000° C., a chromel-alumel couple may be used, and for temperatures below 300° C. a copper constantan thermocouple may be employed. The last two thermocouples are more sensitive than the Pt-PtRh couple.

The cold junction may consist of a pair of mercury filled glass tubes into which the two wires of the thermocouple and the wires to the potentiometer are inserted. The temperature of this junction must be well controlled and this is easily done by immersing both tubes in a vacuum bottle which may be filled with water or a mixture of

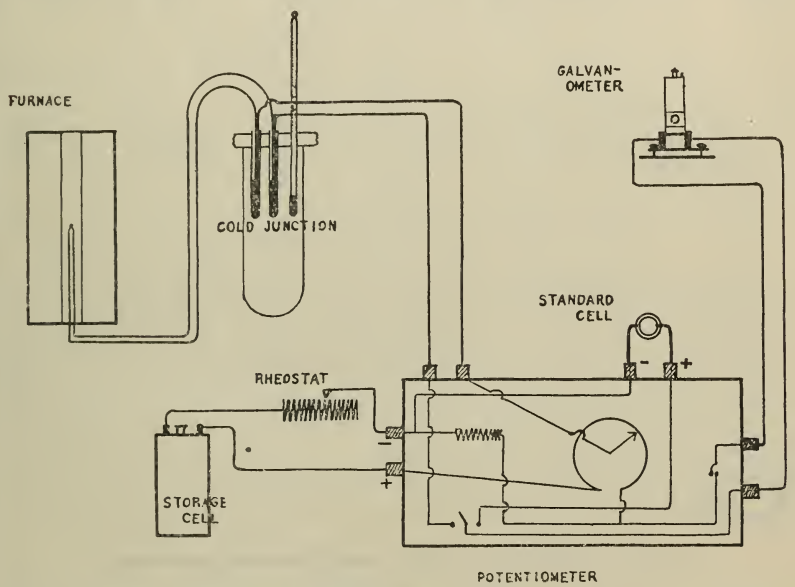

FIGURE 3.—*Potentiometer arrangement*

water and ground ice. The temperature of the cold junction may be read by means of a thermometer.

The galvanometer may be of the quartz suspension, moving concave mirror type, the radius of curvature of the mirror being about 50 cm. The image of a lamp filament is focused on a ground glass placed in such a position that it is convenient for the operator to read, zero being indicated by a black index mark on the ground glass. Lighter reference marks, used to determine the sensitivity, can be advantageously added without confusing the observer. The ground glass should be so arranged that it can be displaced to compensate for small drifts in the zero without readjusting the galvanometer.

A very convenient direct-reading potentiometer indicator may be obtained in which the galvanometer and standard cell are integral parts of the instrument, and a room temperature compensator eliminates the need for a specially controlled cold junction.

3. THE ILLUMINATING VIEWING APPARATUS

Figure 4 is a diagram of the essential optical parts of the viewing apparatus. Light from a source, H, which may be the capillary of a helium tube, or a real image of the same, is made parallel by the lens, L, and after reflection from the prism, R, falls on the interferometer plates, A and B. Here the light partially reflected from the lower surface of A and that from the upper surface of B is returned. That reflected from the upper surface of A is thrown to one side by virtue of the angle of 20′ between the two surfaces of A; and that from the lower surface of B is diffused, or reflected to one side in the same manner as that from the top of A. The reflected beams, from A lower and B upper, return nearly on their incident path and are brought to focus in two real images, both of which must fall on the opening in the

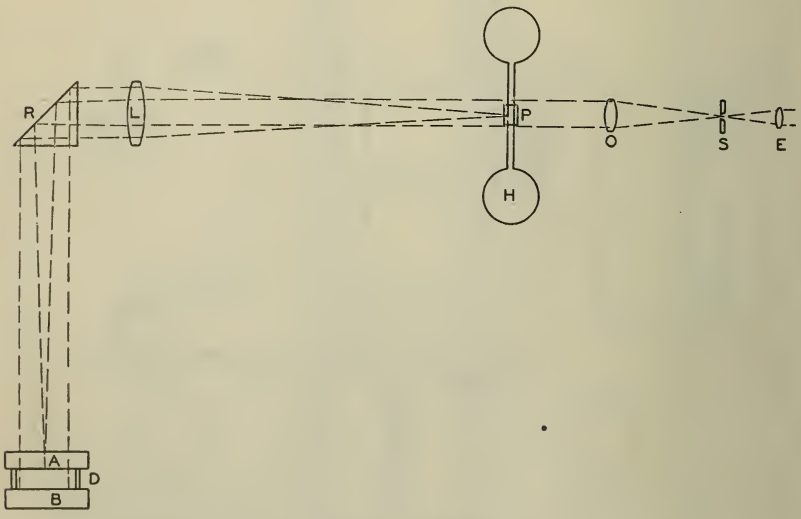

FIG. 4.—*Diagram of optical parts of viewing instrument*

diaphragm at P. When the central rays of these images are parallel, the telescope OSE focused for infinity will focus the fringes in the same plane as the image of the plates. This brings the reference mark on the lower surface of A into focus without parallax between it and the fringes.[2] If two trains of waves from one point in a source having traveled different paths fall upon a point in the retina of the eye, the resultant amplitude of vibration determines the brightness. If they are "in step" maximum brightness results. If, however, the "troughs" of one arrive with the "crests" of the other, destructive interference takes place resulting in relative darkness. If the two trains travel different distances, so that the difference in path is some whole number of wave lengths, then the waves will reach the eye in phase. If the difference in path is equal to some whole number of wave lengths plus one-half wave length, the waves in the two trains will be in

[2] See footnote 2 on p. 65.

opposite phase, so that destructive interference will take place.[2] In order that these conditions may be satisfied, the source H and the plate A must both be at the focal distance of the lens L from L. A small amount of deviation from these conditions may be compensated for by changing the focus of the telescope.

The lens L should be slightly canted so that light reflected from its surfaces will be thrown out of the field, and the prism R should, for the same reason, be slightly rotated about an axis normal to the plane of its hypotenuse.

The following procedure is recommended:

O, the objective of the telescope, should be brought close enough to P to take in a large part of the two interfering beams from A and B. The telescope should be previously focused on a distant object; and the cross wires, S, placed at the principal focus of O. Then, with H at the principal focus of L, the distance from L to A via R can be correctly adjusted by raising or lowering a well illuminated object in the path of the beam until it is in focus when viewed through the whole system The larger plate, B, is then substituted for this object; the eyepiece, E, removed and the light reflected from the upper surface of B brought into the field. If A, the smaller plate, is then laid directly on B and the eyepiece replaced, a set of fringes will be seen. Likewise, any reference marks or other features on the surfaces of either of these plates will be seen to be in focus.

In order to energize the helium tube a high voltage current is needed. This is conveniently supplied by a 110 to 12,000 volt transformer of the kind used for the smaller neon signs. In order to prevent overheating the tube, thus shortening its life, it is well to introduce a resistance of 100 to 150 ohms in series with the primary of the transformer. As a criterion, the bulbs at the ends of the helium tube should not, in operation, be too hot to touch. Furthermore, the capillary (which gets hotter than the ends of the tube) should not be allowed to get hot enough to give off sodium light. A conveniently arranged switch will enable one to turn off the light when not in use, thus lengthening the life of the tube.

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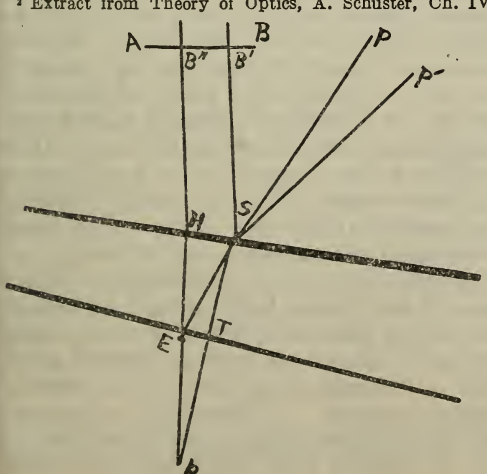
[2] Extract from Theory of Optics, A. Schuster, Ch. IV, p. 76.



The simplest case of a film of variable thickness would be presented by a transparent wedge (fig. 45).

A plane wave AB falling on the wedge, we may select one ray $B'S$ reflected at S toward P, and another, $B''H$, such that after refraction at H and reflexion at E, it meets the upper surface at the same point S. Owing to the inclination of the two surfaces, the refracted ray SP' is not now coincident with SP, though the inclination is small, if the angle of the wedge is small. The difference in optical length between the two rays is $2\mu\epsilon \cos \gamma$ or taking account of the change of phase at reflexion, $2\mu\epsilon \cos \gamma + \frac{\lambda}{2}$. In this expression ϵ denotes the length of the perpendicular from S to the lower surface of the plate (which may be taken as the thickness of the plate at S) and γ is the angle of incidence on the lower surface. The inspection of the figure explains how the expression is derived. Neglecting all rays which have suffered more than one internal reflexion, an eye placed so as to receive both rays SP and SP' and focused on S, will observe a maximum or minimum of light, according as $2\mu\epsilon \cos \gamma$ is an odd or even multiple of half the wave length.

The interferometer plates A and B are of clear transparent fused quartz and should not contain large bubbles or other imperfections. The surfaces of each plate should be flat to one-fifth of a fringe or better throughout the central parts and inclined to each other at an angle of about 20′ for the reasons already explained. It is well to choose A about 27 mm in diameter and B, slightly larger (30 mm). Both A and B should be 4 or 5 mm thick.

III. PREPARATION AND ADJUSTMENT OF THE SPECIMEN

The specimen consists of three elements which are placed between the two interferometer plates A and B in contact with the lower surface of A and the upper surface of B.

1. TYPES OF SAMPLE

The specimen is usually arranged as a tripod, the feet of which may be either projecting parts of the same piece of material, or consist of three separate fragments. Metallic specimens or those already of tubular form (such as glass tubing) are often constructed as rings. Three scallops are, however, taken out of the upper and lower ends of this ring so that the specimen consists effectively of three perpendicular rods of the material joined by three bridgelike arches which do not touch either the top or the bottom plate. (See fig. 4.)

Massive materials which are easily cut and ground are usually made into rough pyramids, tetrahedrons, or cones. The bases of these should be concave or grooved so that each piece rests solidly on three feet. The point of contact with the upper plate should be well within the base limited by these contact points. Three such elements, each sitting solidly on its own feet, constitute a single specimen in which the expansion obtained from a reference mark in the center of the upper plate is an average of the expansions of all three.[3]

2. METHODS OF PREPARATION

Some of the softer terra cottas and clays can be roughed into shape with a file or even scraped with a knife; harder ones must be ground on a carborundum wheel, while glass and the harder ceramic materials can be best formed on a revolving cast-iron lap charged with carborundum powder in water. For shaping many of the small specimens it is very convenient to use a dentists' grinding motor with flexible shaft and a variety of steel and carborundum cutters. After bringing the three elements within a few hundredths of a millimeter of the same height in one of these ways, they are usually finished on a dry carborundum knife stone of rather fine grain. The most advantageous length for the specimen is between 5 and 10 mm.

A particular problem is presented in the preparation of glaze samples. In this case a sample of the glazed body should be broken up and a piece bearing an uncracked flake of glaze 3 or 4 mm long and perhaps half as wide, selected. The body is then ground away and the sample inspected with a microscope to insure the removal of all traces of undissolved body material. A binocular microscope is preferable for this purpose. This flake, which may be as thin as 0.2 mm and will probably not be thicker than 0.6 mm is measured

[3] J. Wash. Acad. Sci. vol. 9, No. 10, May 19, 1919.

by means of a micrometer and ground so that it is of the same thickness along one edge ond very nearly plane parallel. It is then placed on a sheet of dark cardboard and very carefully broken with a needle or fine pointed knife into a number of small pieces. Three of these pieces are selected and placed on the lower plate as is done with the larger specimens, but in this case if the fringes are not of the right width, it is better to substitute another piece from the number available than to grind one down. Usually no measurements are made with the micrometer after the flake of glaze is broken into small pieces. The less area these pieces have, the better, as there will be less likelihood of included air films, etc. The only requirement is that they have wide enough bases compared with their heights, to be stable.

3. ADJUSTMENT

When the three elements of a specimen (whether separate pieces or parts of a ring) are the same length as nearly as can be read on a micrometer caliper,[4] they are ready for a trial between the plates. First, the lower plate should be placed in the focus of the viewing apparatus and the reflection from its upper surface found. This is distinguished by being clear and free from shadows of striæ and other imperfections in the interior of the plate. A still better criterion is the following:

If, when the reflection of a surface is found, the upper plate is laid directly on the lower, fringes should be seen at once if the reflection in question is that of the upper surface of *B*. If they do not appear, or are faint and hazy, remove the upper plate and eyepiece of the observing system, and adjust the leveling screws until the reflection of the other surface of *B* comes into the field. Then replace the eyepiece and upper plate, when sharp black fringes should appear at once.

When the reflection of the top surface has been located and the eyepiece is in place, the three elements of the specimen are placed on *B* at the corners of an equilateral triangle. The elements should be moved slightly with the fingers in order to feel any grit which may have eluded the previous cleaning. If any is found, the elements should be removed and cleaned before proceeding. The plate, *A*, is then held slightly above the specimen and turned about a vertical axis into a position such that the refractive effect of the upper plate will not throw the light reflected from the lower plate out of the field. When this position is found, the plate is set gently on top of the specimen. If the micrometer has been used carefully, fringes should be seen at once. If they are not visible, take a glass rod drawn to a point about as fine as an ordinary pencil and press with this carefully on the top plate near the reference mark. If this does not bring fringes into view, inspect the elements carefully to see that none of them has been laid on its side. This is by no means an uncommon occurrence, especially with specimens approximately tetrahedral in shape. If all are found erect, they should be remeasured. It is well to see if any one of them is, perhaps, a whole hundredth or tenth of a millimeter longer than another.

[4] The usual metric micrometer has divisions representing hundredths of a millimeter; an English instrument should have the smallest division 1/1000 inch. An effort should be made in either case to estimate tenths of the smallest division.

When the fringes have been found, press with the glass rod until sure that the plates are resting in a position of stable equilibrium. If the fringes are too wide or too narrow, the elements must be adjusted in length. When a slight pressure is exerted on the upper plate near the reference mark, the fringes move toward the thick side of the space between the plates, that is, toward the longest of the three elements. This indicates which one is to be shortened. It should be remembered that the method by which the elements are now being compared is far more sensitive than the micrometer, hence only a relatively slight change needs to be made.

4. INTRODUCING THE SPECIMEN INTO THE FURNACE

Having the fringes of the desired width, about 2 mm between centers, the plates and specimen, which now constitute an interferometer, may be picked up with a pair of cork-tipped tweezers and placed in the bucket. This bucket should now be lowered carefully into the furnace either by means of a long bail of thin platinum wire permanently attached, or by a pair of internally expanding forceps with small pins made to fit the holes near the upper edge of the bucket. If wire is used, it should be flexible enough to bend easily out of the way. If forceps are used, the lid of the bucket, a porcelain disk with a 2-cm hole in the center, must be put in after the bucket is set in place.

After the specimen has been let down into the furnace and the viewing apparatus adjusted, the glass rod should again be pressed against the center of plate A in order to make certain that nothing has shaken loose during the transfer, and that the interferometer in its container is resting solidly in the furnace. At this time it should be noted which side of the interfererometer is the thicker. The viewing apparatus is then swung to one side, the tube or thimble containing the fused quartz windows W_1 and W_2 put in, the cover with the glass window W_3 placed on top, and the viewing apparatus returned and adjusted.[5]

IV. OBSERVATIONS TO BE MADE BEFORE STARTING THE RUN

1. RECORDING THICK EDGE OF INTERFEROMETER

When making the last test with the glass rod, it is advisable, as already stated, just before closing the furnace, to place the rod near the center of the upper plate and exert a slight downward pressure in order to see that the plate is seated solidly. This pressure produces a slight compression which shifts the fringes slightly toward the thick side of the wedge-shaped space between the two plates. This direction should be noted. The fringes will move in the opposite direction when the specimen expands. It is well to draw a small diagram of the field showing the position of the fringes and the elements of the specimen, indicating which is the thick side of the interferometer.

[5] A convenient arrangement for adjusting specimens and transferring them to the furnace without the necessity for readjusting the viewing apparatus is to have a stand set alongside of the furnace at a height such that specimens on it will be the same distance from the table as they will be when in the furnace. If this stand, or the furnace, or both can be leveled, it is possible to arrange things so that the viewing apparatus may be swung from one position to the other and will need very little or no change to be equally in adjustment for both positions.

2. APERTURE OF IRIS DIAPHRAGM

The most advantageous aperture for the iris diaphragm in the observing system should be determined and the diaphragm set there before starting. This precaution is necessary because a change in the size of aperture shifts the observed position of the fringes, which, during the run, would introduce an error of two-tenths or three-tenths of a fringe. For runs which are to be carried to higher temperatures, the aperture should be small in order to minimize the effect of scattered light from the incandescant furnace. If, during the run, the fringes become faint, the condition can probably be remedied by releveling the viewing instrument rather than by changing the aperture of the diaphragm.

3. INITIAL POSITION OF FRINGES

The position of the reference mark with respect to the nearest fringes should be noted and recorded. If the viewing apparatus has a movable cross wire in the eyepiece, it may be desirable to measure this fraction with some accuracy, as its value is important in the case of the smaller specimens or those of low expansion where the total expansion causes but few fringes to pass. In the case of most specimens, however, where the fringes cross the reference mark in relatively rapid succession, the first fringe to cross may be taken as zero and the temperature at the time of transit used as the "room temperature."

4. BALANCE OF STORAGE CELL AGAINST STANDARD CELL

The storage battery should then be balanced against the standard cell.

5. ZERO SETTING OF GALVANOMETER

The zero setting of the galvanometer can usually be accomplished by moving the ground glass until the zero mark falls under the image of the lamp filament.

6. SENSITIVITY OF GALVANOMETER

After the preceding adjustment the key of the potentiometer should be closed and the galvanometer deflection brought to zero by moving the dials. Then, as a check on the sensitivity, one of the dials should be turned one step and the resulting deflection noted and compared with previous readings.

7. INITIAL TEMPERATURE OF COLD JUNCTION AND FURNACE

The temperature of the cold junction should now be read and the difference, if any, between it and the furnace recorded. Even when using the direct-reading potentiometer indicator which has the room temperature compensator, it is desirable to read and record the room temperature outside the furnace as well as the temperature indicated by the thermocouple.

V. THE RUN

Everything necessary for recording the results should be obtained before turning on the heating current.

1. ADJUSTMENT OF THE HEATING CURRENT

Only experience with the individual furnace will reveal how much current is needed at a given temperature to produce a given heating rate. Complete and accurate records of the heating current, times, and resulting temperatures for a few runs will supply all the data needed for successful regulation. The heating schedule used in calibrating the furnace should be adhered to as closely as possible. Immediately after each observation of temperature, the rate should be calculated and the requisite changes in the heating current made. A schedule of increments may be prepared for a particular furnace, but this should be checked and revised from time to time, since the characteristics of a furnace change as the heating ribbon deteriorates with repeated use.

With specimens of low thermal diffusivity or with thick specimens of materials of any kind, there will be a slower inflow of heat into the specimen, so that the temperature indicated by the thermocouple may exceed the average temperature of the specimen by an amount too great to neglect in cases where it is desirable to measure the expansion under equilibrium conditions with a high degree of accuracy. This is particularly true at the lower temperatures, say from room temperature up 100° or 200°. In order to bring the specimen into equilibrium conditions with the least expenditure of time, it is well to make all specimens as small as is practicable without sacrificing stability or sufficient height. Data for the amount of current necessary for holding the temperature of the furnace constant should also be collected.

2. WATCHING THE FRINGES

It is important that the attention of the observer be constantly on his work, as each passing fringe must be counted. There is no other way of telling after a lapse of time whether the fringe on the reference mark is the first or the fifth to come into this position since the last observation. To be sure, when the heating rate is constant and the form of the expansion curve of the material is known, less continuity of attention is permissible because it is practically certain that the fringes will follow each other at regular intervals; but unusual care should be exercised wherever there is any uncertainty regarding the substance or in the neighborhood of expected changes.

3. PREPARING TO READ THE TEMPERATURE

The potentiometer should be set before an expected temperature reading. The galvanometer is then kept on zero by movements of the dials and at the same time the fringe is watched as it approaches the reference mark. When the fringe is exactly on the mark, the setting of the galvanometer is verified by a quick glance and the dials allowed to remain in that position until read.

VI. RECORDS

Where the temperature is not to be read for every fringe, the time of transit of each fringe should be recorded on a separate sheet of paper.

A convenient record form is shown below:

Substance, glass.

Date. Dec. 1, 1922.
Serial No. S 107.
Run No. 1.
Source. Glass section No. 43

Length of Specimen L_0=0.7640 cm. Value of $\frac{\frac{\lambda}{2}}{L_0}$=0.3845.

Temperature of cold junction $\frac{22°\text{ C.}}{\text{mv } 125}$. Room temperature 23° C.

I	II	III	IV	V	VI	VII	VIII
Transit time	Fringes N	$N\frac{\frac{\lambda}{2}}{L_0}$	Air correction	ΔL in	Potentiometer readings	Corrected for cold junction	Temperature
		μ/cm	μ/cm	μ/cm	*microvolts*	*microvolts*	°C.
12.56	0	0	0	0	6	131	23
1.55	10	3.85	.37	4.22	303	428	70
1.28	20	7.69	.62	8.31	605	730	112

In the first column is written the time of transit of the fringe recorded in the second. In the sixth column is the reading of the potentiometer at that time. In the seventh, this reading is corrected for the temperature of the cold junction.[6] The eighth column is derived from the seventh by means of Table 1 of the appendix. These columns are all filled in during the run. The number of the coming fringe is recorded as soon as it is fully decided it is the next one to be used. As soon as it is centered on the reference mark, the time is read and recorded. Then the potentiometer is read and recorded, the correction added and the temperature found by reference to the calibration table for the thermocouple.

These operations consume time, so care must be exercised that no fringe be allowed to pass unobserved while the attention is distracted. If their movement is very rapid, it may be best to record only the time, number of fringe, and microvolts until the region of rapid expansion has been passed.

VII. COMPUTING AND PLOTTING

The third, fourth, and fifth columns are calculated after completing the run. The values of the third column are obtained by multiplying the number of fringes shown in the second column by a previously calculated factor $\frac{\frac{\lambda}{2}}{L_0}$ the equation:

$$\Delta L = N\frac{\frac{\lambda}{2}}{L_0} + \text{air correction}$$

where N is the number of fringes, λ is the wave length (in microns) of the light used, and $N\frac{\lambda}{2}$ is the apparent amount in microns that the

[6] This is done by adding the number of microvolts equivalent to the temperature of the cold junction to the reading of the dials. If melting ice made from pure water is kept around the cold junction, this correction reduces to zero.

specimen has expanded. When this quantity is divided by the original length of the specimen, L_0, in centimeters, we have ΔL, the expansion of a centimeter of the material in microns.[7] To facilitate the calculations, the factor $\frac{\frac{\lambda}{2}}{L_0}$ is calculated separately. $\frac{\lambda}{2}$ for the yellow helium line is 0.29378μ. at 15° C. and 760 mm. The expression $N\frac{\frac{\lambda}{2}}{L_0}$ does not give the true dilatation because the wave length of the

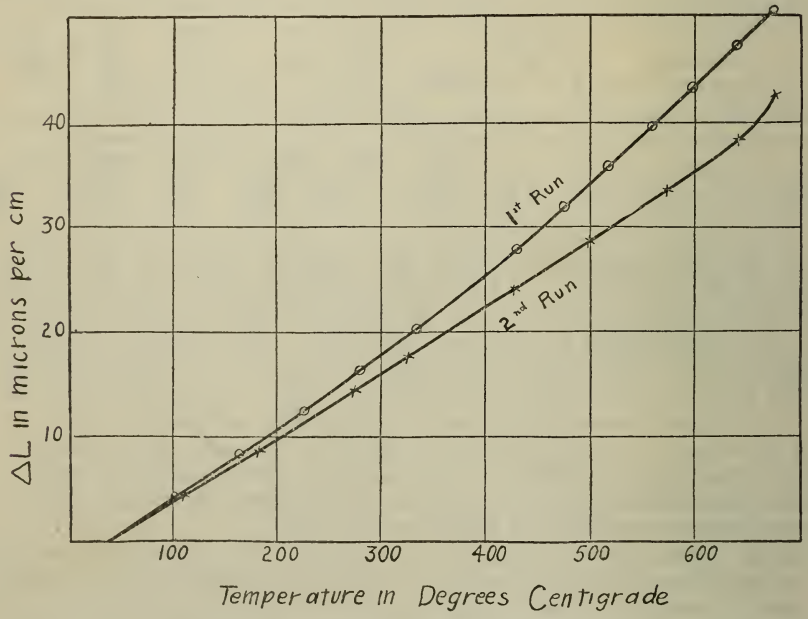


FIGURE 5.—*Sample thermal expansion curve*

light is affected by the temperature and pressure [8] of the air between the two plates. To correct for changes in temperature, Table 2 (see Appendix), has been calculated from the data of Scientific Paper No. 327. If the first temperature recorded is above 20° C. the entry in the table opposite that number should be subtracted from each of the succeeding corrections. These corrections should be entered in the fourth column. The fifth column is the sum of the third and fourth.

In plotting, the temperatures are laid off along the horizontal axis and the dilatation along the vertical axis. The fifth column is then plotted against the eighth and the resulting graph is the expansion curve of the substance. An example is shown in Figure 5. The average coefficient of expansion for any temperature range is usually, for reasons of convenience, expressed in parts per million. To obtain

[7] This is equivalent to "parts per ten thousand" or "hundredths of a per cent."
[8] The effect of changes in pressure usually encountered during a run is negligible.

the average coefficient of expansion for a certain temperature range, it is necessary to divide the change in length expressed in parts per million by the number of degrees in this particular temperature range. For example, the average coefficient of expansion of iron between 20° and 100° C. is 12 parts per 1,000,000 per °C. This may also be expressed as 12×10^{-6} or 0.000012 per °C.

VIII. APPENDIX

TABLE I.—*Reference table for Pt. to Pt.–10 per cent Rh thermocouple*

Emf-temperature relation for platinum to platinum–10 per cent rhodium thermocouples as calculated by Adams [1] from gas thermometer determinations made at the Geophysical Laboratory by Day and Sosman.

[Emfs are expressed in microvolts and temperatures in °C. Cold junctions at 0° C.]

E Microvolts	0	1,000	2,000	3,000	4,000	5,000	6,000	7,000	8,000
0	0	147.1	265.4	374.3	478.1	578.3	675.3	769.5	861.1
	17.8	*12.6*	*11.2*	*10.6*	*10.2*	*9.8*	*9.5*	*9.3*	*9.0*
100	17.8	159.7	276.6	384.9	488.3	588.1	684.8	778.8	870.1
	16.7	*12.4*	*11.1*	*10.5*	*10.1*	*9.8*	*9.5*	*9.2*	*9.0*
200	34.5	172.1	287.7	395.4	498.4	597.9	694.3	788.0	879.1
	15.8	*12.2*	*11.0*	*10.5*	*10.1*	*9.8*	*9.5*	*9.2*	*9.0*
300	50.3	184.3	298.7	405.9	508.5	607.7	703.8	797.2	888.1
	15.1	*12.0*	*11.0*	*10.4*	*10.1*	*9.7*	*9.5*	*9.2*	*9.0*
400	65.4	196.3	309.7	416.3	518.6	617.4	713.3	806.4	897.1
	14.6	*11.8*	*10.9*	*10.4*	*10.0*	*9.7*	*9.4*	*9.2*	*9.0*
500	80.0	208.1	320.6	426.7	528.6	627.1	722.7	815.6	906.1
	14.1	*11.6*	*10.9*	*10.4*	*10.0*	*9.7*	*9.4*	*9.1*	*8.9*
600	94.1	219.7	331.5	437.1	538.6	636.8	732.1	824.7	915.0
	13.7	*11.5*	*10.8*	*10.3*	*10.0*	*9.7*	*9.4*	*9.1*	*8.9*
700	107.8	231.2	342.3	447.4	548.6	646.5	741.5	833.8	923.9
	13.4	*11.5*	*10.7*	*10.3*	*9.9*	*9.6*	*9.4*	*9.1*	*8.9*
800	121.2	242.7	353.0	457.7	558.5	656.1	750.9	942.9	932.8
	13.1	*11.4*	*10.7*	*10.2*	*9.9*	*9.6*	*9.3*	*9.1*	*8.8*
900	134.3	254.1	363.7	467.9	568.4	665.7	760.2	852.0	941.6
	12.8	*11.3*	*10.6*	*10.2*	*9.9*	*9.6*	*9.3*	*9.1*	*8.8*
1,000	147.1	265.4	374.3	478.1	578.3	675.3	769.5	861.1	950.4

E Microvolts	9,000	10,000	11,000	12,000	13,000	14,000	15,000	16,000	17,000
0	950.4	1,037.3	1,122.2	1,205.9	1,289.3	1,372.4	1,454.8	1,537.5	1,620.9
	8.8	*8.6*	*8.4*	*8.3*	*8.4*	*8.3*	*8.2*	*8.3*	*8.3*
100	959.2	1,045.9	1,130.6	1,214.2	1,297.7	1,380.7	1,463.0	1,545.8	1,629.2
	8.8	*8.5*	*8.4*	*8.4*	*8.3*	*8.3*	*8.2*	*8.3*	*8.4*
200	968.0	1,054.4	1,139.0	1,222.6	1,306.0	1,389.0	1,471.2	1,554.1	1,637.6
	8.7	*8.5*	*8.4*	*8.3*	*8.3*	*8.3*	*8.2*	*8.3*	*8.3*
300	976.7	1,062.9	1,147.4	1,230.9	1,314.3	1,397.3	1,479.4	1,562.4	1,645.9
	8.7	*8.5*	*8.4*	*8.4*	*8.3*	*8.3*	*8.3*	*8.4*	*8.4*
400	985.4	1,071.4	1,155.8	1,239.3	1,322.6	1,405.6	1,487.7	1,570.8	1,654.3
	8.7	*8.5*	*8.4*	*8.3*	*8.3*	*8.2*	*8.3*	*8.3*	*8.3*
500	994.1	1,079.9	1,164.2	1,247.6	1,330.9	1,413.8	1,496.0	1,579.1	1,662.6
	8.7	*8.5*	*8.3*	*8.3*	*8.3*	*8.2*	*8.3*	*8.4*	*8.3*
600	1,002.8	1,088.4	1,172.5	1,255.9	1,339.2	1,422.0	1,504.3	1,587.5	1,670.9
	8.7	*8.5*	*8.4*	*8.4*	*8.3*	*8.2*	*8.3*	*8.3*	*8.4*
700	1,011.5	1,096.9	1,180.9	1,264.3	1,347.5	1,430.2	1,512.6	1,595.8	1,679.3
	8.6	*8.5*	*8.3*	*8.3*	*8.3*	*8.2*	*8.3*	*8.4*	*8.3*
800	1,020.1	1,105.4	1,189.2	1,272.6	1,355.8	1,438.4	1,520.9	1,604.2	1,687.6
	8.6	*8.4*	*8.4*	*8.4*	*8.3*	*8.2*	*8.3*	*8.3*	*8.4*
900	1,028.7	1,113.8	1,197.6	1,281.0	1,364.1	1,446.6	1,529.2	1,612.5	1,696.0
	8.6	*8.4*	*8.3*	*8.3*	*8.3*	*8.2*	*8.3*	*8.4*	*8.3*
1,000	1,037.3	1,122.2	1,205.9	1,289.3	1,372.4	1,454.8	1,537.5	1,620.9	1,704.3

[1] J. Am. Chem. Soc., vol. 36, p. 65; 1914; Int. Crit. Tables, vol. 1, p. 57; 1926.

TABLE 2.—*Air corrections from 20° C. to λ temperatures indicated (microns per centimeter)*

[Atmospheric pressure, 760 mm]

Temperature	Corrections	Temperature	Corrections	Temperature	Corrections	Temperature	Corrections	Temperature	Corrections	Temperature	Corrections
20	0.00	70	0.40	142	0.80	252	1.20	439	1.60	840	2.00
1	.01	2	.41	4	.81	5	1.21	446	1.61	850	2.01
2	.02	4	.42	6	.82	8	1.22	453	1.62	870	2.02
3	.03	5	.43	8	.83	263	1.23	9	1.63	880	2.03
4	.04	6	.44	150	.84	6	1.24	466	1.64	900	2.04
5	.05	8	.45	4	.85	9	1.25	470	1.65	920	2.05
6	.06	80	.46	6	.86	273	1.26	480	1.66	940	2.06
7	.07	2	.47	8	.87	7	1.27	7	1.67	960	2.07
8	.08	3	.48	160	.88	280	1.28	493	1.68	980	2.08
9	.09	4	.49	3	.89	5	1.29	502	1.69	1,000	2.09
30	.10	6	.50	5	.90	9	1.30	510	1.70	1,020	2.10
2	.11	8	.51	8	.91	292	1.31	7	1.71	1,040	2.11
3	.12	9	.52	170	.92	6	1.32	521	1.72	1,060	2.12
5	.13	90	.53	3	.93	300	1.33	534	1.73	1,080	2.13
6	.14	2	.54	5	.94	5	1.34	542	1.74	1,100	2.14
7	.15	4	.55	8	.95	9	1.35	551	1.75		
8	.16	6	.56	180	.96	313	1.36	9	1.76		
40	.17	7	.57	3	.97	7	1.37	568	1.77		
1	.18	8	.58	5	.98	320	1.38	578	1.78		
2	.19	102	.59	8	.99	6	1.39	587	1.79		
3	.20	3	.60	190	1.00	331	1.40	596	1.80		
5	.21	4	.61	4	1.01	5	1.41	606	1.81		
6	.22	6	.62	7	1.02	340	1.42	615	1.82		
7	.23	8	.63	200	1.03	3	1.43	620	1.83		
8	.24	110	.64	2	1.04	350	1.44	635	1.84		
50	.25	2	.65	5	1.05	4	1.45	646	1.85		
1	.26	4	.66	8	1.06	9	1.46	657	1.86		
2	.27	6	.67	210	1.07	364	1.47	668	1.87		
4	.28	8	.68	4	1.08	9	1.48	679	1.88		
5	.29	9	.69	7	1.09	374	1.49	690	1.89		
6	.30	122	.70	220	1.10	8	1.50	700	1.90		
7	.31	4	.71	3	1.11	386	1.51	712	1.91		
9	.32	6	.72	6	1.12	392	1.52	726	1.92		
61	.33	8	.73	9	1.13	7	1.53	740	1.93		
3	.34	130	.74	232	1.14	403	1.54	752	1.94		
4	.35	2	.75	5	1.15	9	1.55	766	1.95		
65	.36	4	.76	8	1.16	415	1.56	780	1.96		
6	.37	6	.77	241	1.17	421	1.57	790	1.97		
8	.38	8	.78	5	1.18	7	1.58	810	1.98		
9	.39	140	.79	9	1.19	433	1.59	820	1.99		

TABLE 3.—*Air corrections from 20° C. to low temperatures indicated (microns per centimeter)*

Atmospheric pressure, 760 mm.

Temperature	Correction	Temperature	Correction	Temperature	Correction	Temperature	Correction	Temperature	Correction	Temperature	Correction
+20	0.00	−20	−0.43	−60	−1.02	−100	−1.89	−140	−3.27	−180	−5.85
19	−.01	21	.44	61	1.04	101	1.91	141	3.32	181	5.94
18	.02	22	.45	62	1.06	102	1.94	142	3.36	182	6.04
17	.03	23	.47	63	1.07	103	1.97	143	3.41	183	6.13
16	.04	24	.48	64	1.09	104	1.99	144	3.46	184	6.23
15	.05	25	.49	65	1.11	105	2.02	145	3.50	185	6.33
14	.06	26	.51	66	1.13	106	2.05	146	3.55	186	6.44
13	.07	27	.52	67	1.15	107	2.08	147	3.60	187	6.54
12	.08	28	.53	68	1.17	108	2.11	148	3.65	188	6.65
11	.09	29	.55	69	1.19	109	2.14	149	3.71	189	6.76
10	.10	30	.56	70	1.21	110	2.17	150	3.76	190	6.88
9	.11	31	.57	71	1.22	111	2.20	151	3.81	191	7.00
8	.12	32	.59	72	1.24	112	2.23	152	3.86	192	7.12
7	.13	33	.60	73	1.26	113	2.26	153	3.92	193	7.24
6	.14	34	.61	74	1.28	114	2.29	154	3.98	194	7.36
5	.15	35	.63	75	1.30	115	2.32	155	4.03		
4	.16	36	.64	76	1.32	116	2.36	156	4.09		
3	.17	37	.66	77	1.35	117	2.39	157	4.15		
2	.18	38	.67	78	1.37	118	2.42	158	4.21		
1	.19	39	.69	79	1.39	119	2.45	159	4.27		
0	.20	40	.70	80	1.41	120	2.49	160	4.33		
−1	.21	41	.71	81	1.43	121	2.52	161	4.39		
2	.22	42	.73	82	1.45	122	2.56	162	4.46		
3	.23	43	.74	83	1.47	123	2.59	163	4.52		
4	.24	44	.76	84	1.50	124	2.63	164	4.59		
5	.25	45	.78	85	1.52	125	2.66	165	4.66		
6	.26	46	.79	86	1.54	126	2.70	166	4.73		
7	.28	47	.81	87	1.56	127	2.74	167	4.80		
8	.29	48	.82	88	1.59	128	2.78	168	4.87		
9	.30	49	.84	89	1.61	129	2.81	169	4.94		
10	.31	50	.85	90	1.63	130	2.85	170	5.02		
11	.32	51	.87	91	1.66	131	2.89	171	5.09		
12	.33	52	.89	92	1.68	132	2.93	172	5.17		
13	.35	53	.90	93	1.71	133	2.97	173	5.25		
14	.36	54	.92	94	1.73	134	3.01	174	5.33		
15	.37	55	.94	95	1.76	135	3.05	175	5.41		
16	.38	56	.95	96	1.78	136	3.10	176	5.49		
17	.39	57	.97	97	1.81	137	3.14	177	5.58		
18	.41	58	.99	98	1.83	138	3.18	178	5.67		
19	.42	59	1.00	99	1.86	139	3.23	179	5.76		

1. COMPUTATIONS RELATING TO OXIDIZABLE SPECIMENS

In some cases, where the expansion of an oxidizable specimen is desired and the formation of an oxide film during the run causes a spurious expansion to be introduced, the true expansion may often be obtained by running two sets of specimens of different lengths of the same material. The true expansion may then be calculated by the following method, assuming that the oxide film is the same in both cases.

Two samples are made up, S_1 and S_2. In this case $S_1 = 0.22$ cm and $S_2 = 0.37$ cm at 20° C.

Over a temperature range (for example, 20° to 500°), S_1 shows an apparent increase of 73.5 μ/cm and S_2 shows an apparent increase of 70.0 μ/cm.

Apparent increase of S_1 $S_1 = 73.5 \times 0.22 = 16.17$.
Apparent increase of S_2 $S_2 = 70.0 \times 0.37 = 25.90$.

$$S_1 = S_1 \times C \times (t_2 - t_1) + R \tag{1}$$

where C = average coefficient expansion between t_1 and t_2 and R = oxide film.

$$S_2 = S_2 \times C \times (t_2 - t_1) + R \tag{2}$$

Subtract equation (1) from equation (2) after substituting numerical values.

$$\begin{aligned} 16.17 &= 0.22 \times C \times 480 + R \\ 25.90 &= 0.37 \times C \times 480 + R \\ \overline{9.73} &= \overline{(0.37 - 0.22) \times C \times 480} \\ C &= \frac{9.73}{0.15 \times 480} = 13.5 \ \mu\text{/cm or } 13.5 \times 10^{-6}. \end{aligned}$$

Washington, October, 1932.